Physics 2: Electricity & Magnetism – Sources of the Magnetic Field

Part 2

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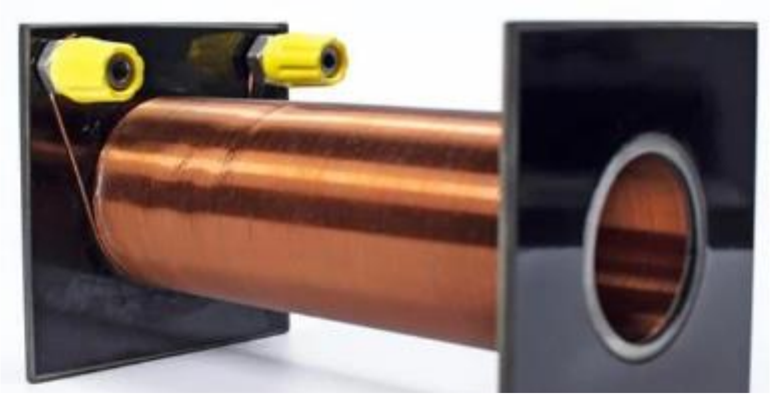

https://www.arborsci.com/products/air-core-solenoid-5a-max

Outline

-The Biot–Savart Law: Able to calculate the magnetic field due to various current distributions

-The Magnetic Force Between Two Parallel Conductors

-Ampère’s Law: Useful in calculating the magnetic field of a highly symmetric configuration carrying a steady current

-The Magnetic Field of a Solenoid

-Gauss’s Law in Magnetism

-Magnetism in Matter

-Problems and Solutions

Gauss's Law in Magnetism

- The flux associated with a magnetic field is defined in a manner similar to that used to define electric flux
- Consider $d\vec{A}$ element in an arbitrarily shaped surface in Fig. 30.19($d\vec{A}$ ⊥ surface). If the magnetic field at this element is $\vec{B}$, the magnetic flux through the surface is:

$$\emptyset_B = \int \vec{B}.d\vec{A}$$

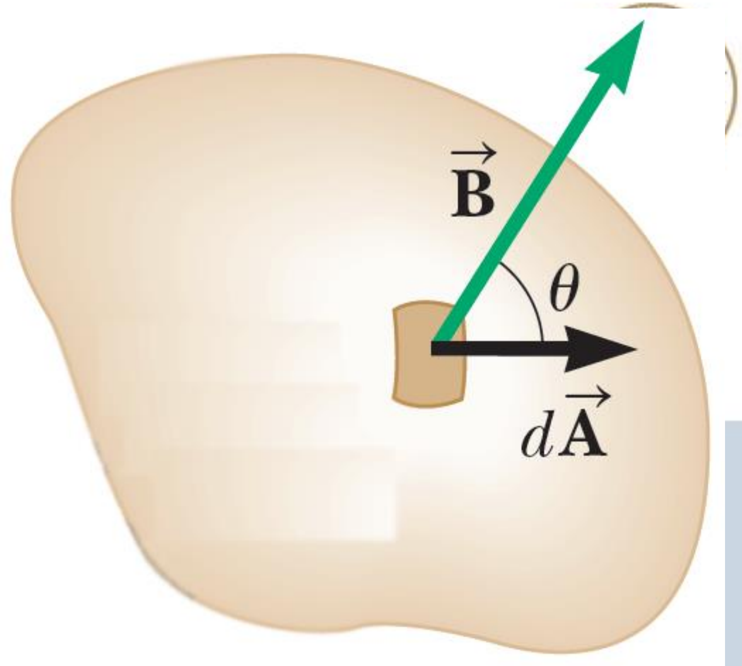

Fig. 30.19

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For a plane of area *A* in a uniform magnetic field, magnetic flux is:

$$\emptyset_B = BAcos\theta$$

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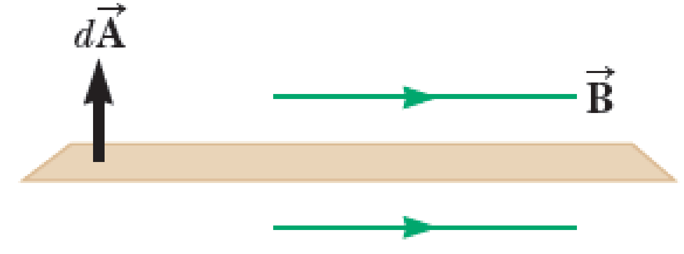
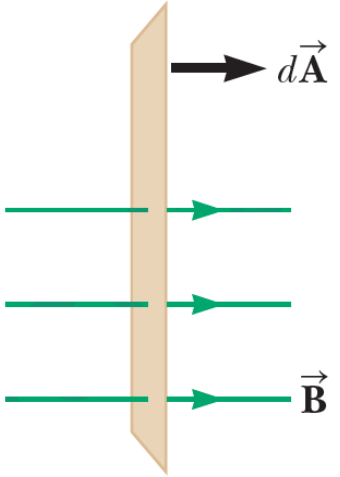
- The flux through the plane is zero when the magnetic field is parallel to the plane surface. The flux through the plane is maximum and is equal to BA when the magnetic field is perpendicular to the plane.





- The unit of magnetic flux is Tm^2, which is defined as a weber (Wb).

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Example 30.7 **Magnetic flux through a rectangular loop**

A rectangular loop of width *a* and length *b* is located near a long wire carrying a current *I* (Fig. 30.21). The distance between the wire and the closest side of the loop is *c.* The wire is parallel to the long side of the loop. Find the total magnetic flux through the loop due to the current in the wire.

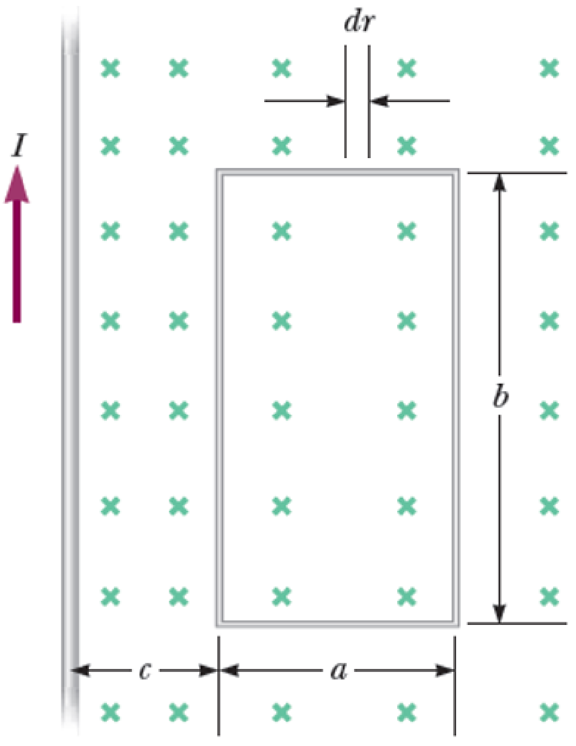

Fig. 30.21

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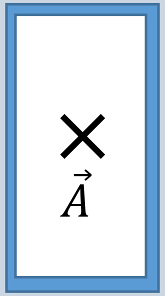
Solution: *B* is parallel to d*A* at any point within the loop.



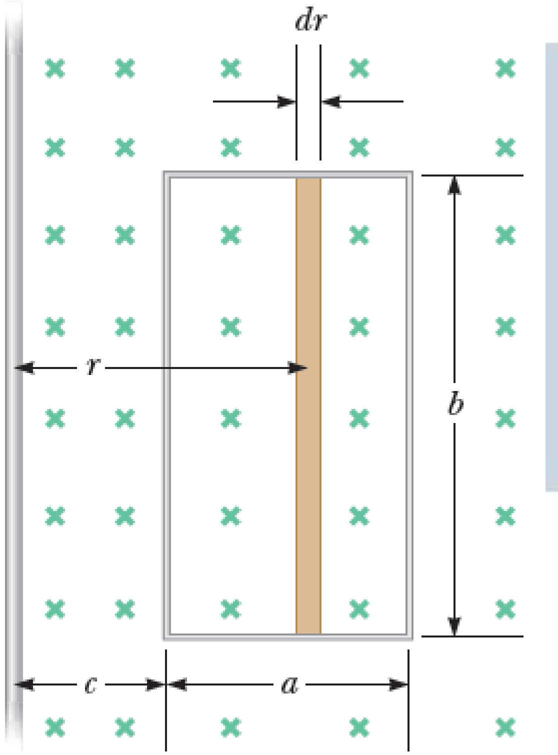
$$\Phi_B = \int \vec{\mathbf{B}} \cdot d\vec{\mathbf{A}} = \int B\,dA = \int \frac{\mu_0 I}{2\pi r}\,dA$$

$$dA = bdr$$

$$\Phi_B = \int \frac{\mu_0 I}{2\pi r}\,b\,dr = \frac{\mu_0 I b}{2\pi}\int \frac{dr}{r}$$

$$\Phi_B = \frac{\mu_0 I b}{2\pi}\int_c^{a+c} \frac{dr}{r} = \frac{\mu_0 I b}{2\pi}\ln r\Big|_c^{a+c}$$

$$= \frac{\mu_0 I b}{2\pi}\ln\left(\frac{a+c}{c}\right) = \boxed{\frac{\mu_0 I b}{2\pi}\ln\left(1+\frac{a}{c}\right)}$$

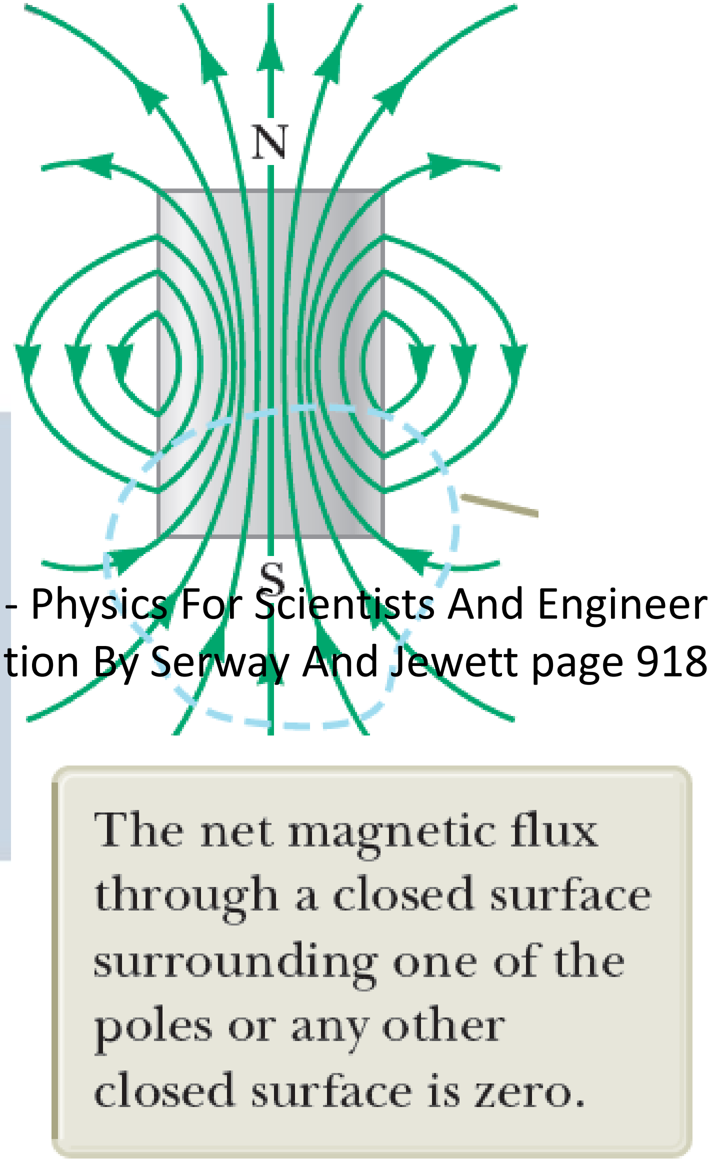


If *c* is very large, the flux approaches zero. If *c* goes to zero, the flux becomes infinite.

- In Chapter 24, we have found that the electric flux through a closed surface surrounding a net charge is proportional to that charge (Gauss's law). This behaviour exists because electric field lines originate and terminate on electric charges.
- This situation is quite different for magnetic fields. Magnetic field lines do not begin or end at any point. For any closed surface such as in Fig. 30.22, magnetic field lines entering the surface equals the number leaving the surface, therefore, the net magnetic flux is zero.
- Gauss's law in magnetism states that the net magnetic flux through any closed surface is always zero.

$$\boxed{\oint \vec{B}.d\vec{A} = 0}$$

- This statement represents that isolated magnetic poles (monopoles) have never been detected and perhaps do not exist.



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The net magnetic flux through a closed surface surrounding one of the poles or any other closed surface is zero.

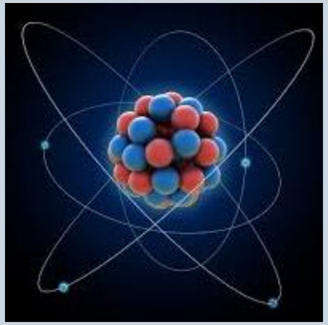
Fig. 30.22

30.6 Magnetism in Matter

Any current loop has a magnetic field and therefore has a magnetic dipole moment, including the atomic-level current loops.

The Magnetic Moments of Atoms

Let’s begin our discussion with a classical model of the atom in which electrons move in *circular* orbits around massive nucleus. A moving electron constitutes a tiny current loop in this model. Assume that electron is a particle making uniform circular motion. The current associated with this orbiting electron is



https://www.thoughtco.com/most-basic-building-block-of-matter-608358

$$I = \frac{e}{T} = \frac{e\upsilon}{2\pi r}$$

The magnitude of the magnetic moment associated with this current loop is given by

$$\mu = IA = \left(\frac{e\upsilon}{2\pi r}\right)\pi r^2 = \frac{1}{2} e\upsilon r$$

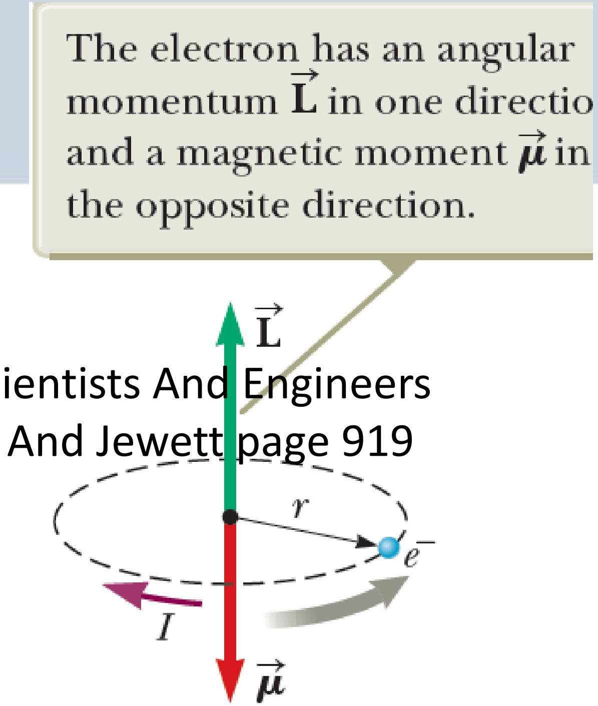
- Because the magnitude of the orbital angular momentum of the electron is given by $L = m_e vr$ (Eq. 11.12), the magnetic moment can be written as,

$$\mu = IA = \left(\frac{e\upsilon}{2\pi r}\right)\pi r^2 = \frac{1}{2} e \frac{L}{m_e r} r = \left(\frac{e}{2m_e}\right) L$$

- This result demonstrates that the magnetic moment of the electron is proportional to its orbital angular momentum. Because the electron is negatively charged, the vectors μ and L point in opposite directions.

- Orbital angular momentum is quantized and is equal to multiples of Planck's constant. The smallest nonzero value of the electron's magnetic moment resulting from its orbital motion isÇ

$$\mu = \sqrt{2}\,\frac{e}{2m_e}\hbar$$


The electron has an angular momentum $\vec{\mathbf{L}}$ in one directio and a magnetic moment $\vec{\boldsymbol{\mu}}$ in the opposite direction.

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Because all substances contain electrons, why most substances are not magnetic?

- The main reason is that, in most substances, the magnetic moment of one electron in an atom is canceled by that of another electron orbiting in the opposite direction. The net result is that, for most materials, the magnetic effect produced by the orbital motion of the electrons is either zero or very small.
- In addition to its orbital magnetic moment, an electron (as well as protons, neutrons, and other particles) has an intrinsic property called **spin** that also contributes to its magnetic moment. Classically, the electron might be viewed as spinning about its axis as shown in Figure 30.25. Spin angular momentum of an electron is $\vec{S} = \frac{\sqrt{3}}{2}\hbar$

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- The magnetic moment characteristically associated with the spin of an electron has the value

$$\mu_{spin} = \frac{e}{2m_e}\hbar$$

This is called **Bohr magneton**. Atomic magnetic moments can be expressed as multiples of Bohr magneton.

- In atoms containing many electrons, the electrons usually pair up with their spins opposite each other; thus, the spin magnetic moments cancel. However, atoms containing an odd number of electrons must have at least one unpaired electron and therefore some spin magnetic moment.

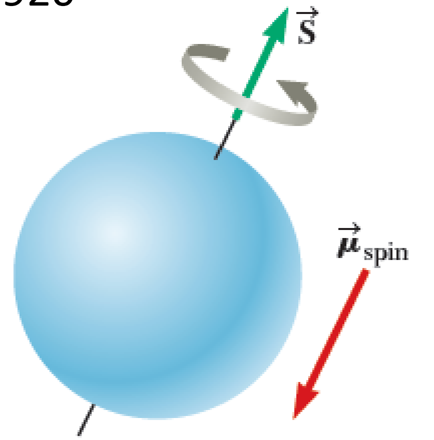
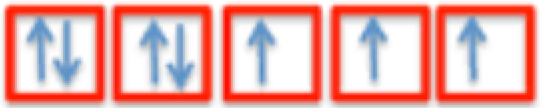


Figure 30.25

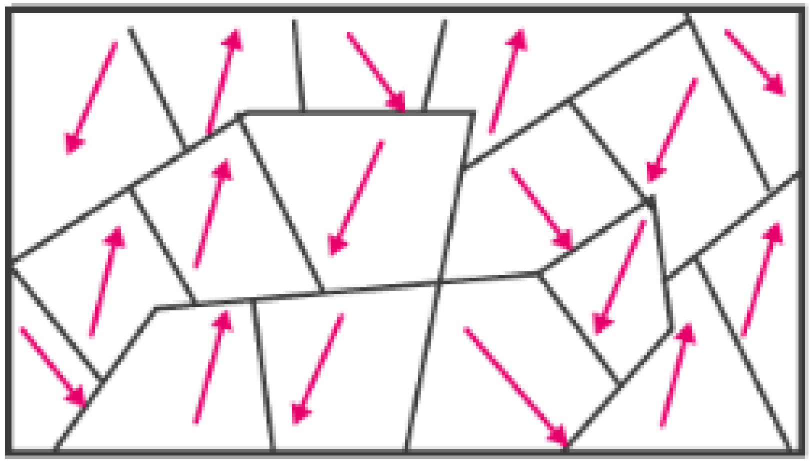


Classification of Magnetic Substances

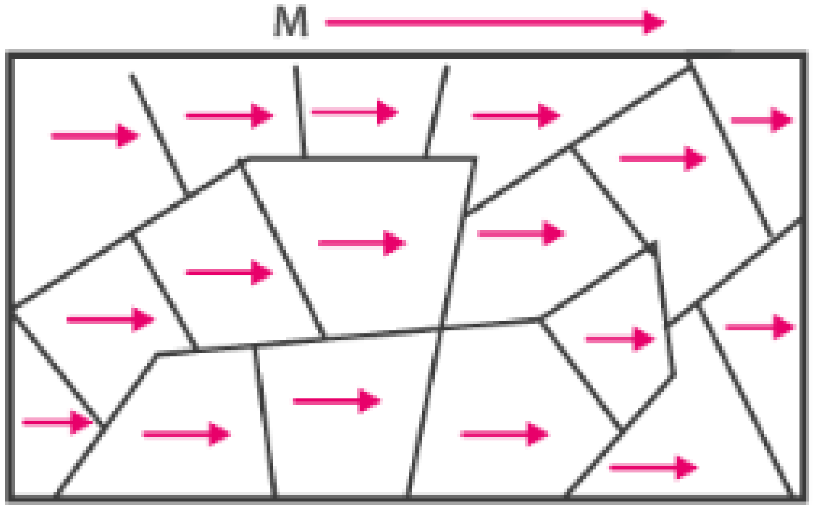
- Substances can be classified as belonging to one of three categories, depending on their magnetic properties. Paramagnetic and **ferromagnetic** materials are those made of atoms that have permanent magnetic moments. Diamagnetic materials are those made of atoms that do not have permanent magnetic moments.

Ferromagnetic Materials

- Iron, cobalt, nickel.. are ferromagnetic materials. All ferromagnetic materials are made up of microscopic regions called **domains,** regions within which all magnetic moments are aligned.



A. Random domain orientation



B. After magnetization

- When the temperature of a ferromagnetic substance reaches or exceeds a critical temperature called the **Curie temperature**, the substance loses its residual magnetization.

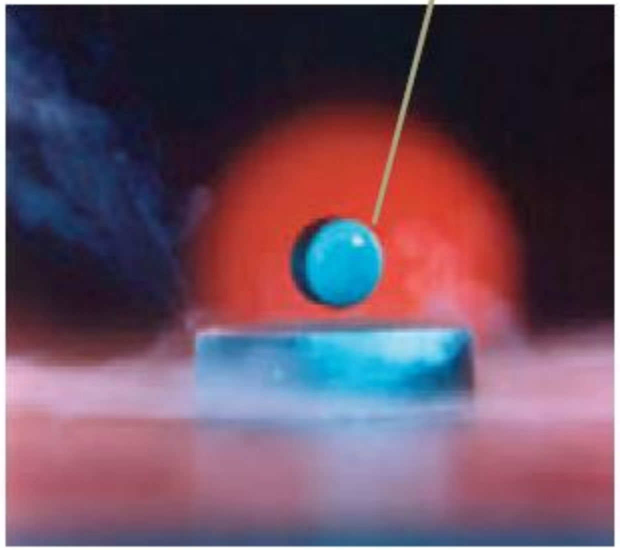
Paramagnetic Materials

Paramagnetic materials have a weak magnetism resulting from the presence of atoms that have permanent magnetic moments. These moments interact only weakly with one another and are randomly oriented in the absence of an external magnetic field.

Diamagnetic Materials

When an external magnetic field is applied to a diamagnetic substance, a weak magnetic moment is induced in the direction opposite the applied field, causing diamagnetic materials to be weakly repelled by a magnet. (left image)

superconducting disk.



Courtesy Argonne National Laboratory

Figure 30.27 An illustration of the Meissner effect, shown by this magnet suspended above a cooled ceramic superconductor disk, has become our most visual image of high-temperature superconductivity.

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Summary

- The Biot–Savart law
- The magnetic force per unit length between two parallel wires separated by a distance a
- Ampère’s law
- The magnitude of the magnetic field at a distance r from a long, straight wire carrying an electric current I
- The magnitudes of the fields inside a toroid and solenoid
- Gauss’s law of magnetism
- Classification of magnetic substances